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Evolutionary Analysis of the Relationship between Economic Growth, Environmental Quality and Resource Scarcity

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1. Motivation and assumptions

The analysis of economic growth is dominated by neoclassical aggregate models of exogenous and endogenous growth in equilibrium. This is also true for applications of growth theory to environmental problems and resource scarcity. Although these have generated many clear insights, they suffer from two problems. First, they do not address all relevant issues related to growth, because they omit certain elements in their description of reality: out of equilibrium processes; 'choice' between multiple equilibria; and, structural changes in the economy. The latter is the more surprising given that economic growth in reality hardly ever occurs without structural change. A second problem with growth theory is that it makes many assumptions that are convenient but erroneous, in which case its results are questionable at best. Representative agents, rational behavior, perfect information, an aggregate production function, growth in equilibrium, and reversible growth are all debatable, to say the least. Moreover, due to these assumptions certain policy relevant aspects disappear from the analysis.

This chapter starts from a set of alternative assumptions, offered by evolutionary growth theory, which is part of evolutionary economics. The thematic core of evolutionary economics can be characterized in various ways: interaction of innovation and selection; changing populations of heterogeneous agents; the impact of economic distribution on economic dynamics; and agents characterized by adaptive routines and imitation. Attention is focused on the link between evolutionary growth theory and scarcity. The analysis of resource scarcity and environmental pollution in the framework of growth theory during the 1970s has entirely occurred within the domain of standard growth theory. Since the 1980s, growth has been studied from the perspective of evolutionary theories of growth and technical change. This has, however, hardly influenced environmental and resource economics.

Evolutionary growth theory employs micro-level descriptions of populations of firms resulting in non-equilibrium, differential growth with continuous interaction between innovation and selection of diversity. This allows for a subtle, realistic, and really long-run relationship between resource scarcity, environmental conditions and economic growth. It can address the fact that growth virtually always goes along with changes in the underlying distributions of technologies and firms. The notion of coevolution is relevant for both historical and future growth analysis in that the economy is seen as adaptive to the environment and vice versa. It will further be shown that (co)evolutionary growth should not be equated to progress. Finally, evolution means that the link between a social optimum and a market equilibrium is lost, implying that optimal public policy – focusing on resource exploitation and environmental externalities – receives little attention in evolutionary economics. On the other hand, evolutionary theory is well able to address the dynamic implications of population diversity and distribution issues, as well as policies for innovation incentives and (altering) selection forces. All these issues will receive attention here.

The organization of this chapter is as follows. Section 2 discusses general characteristics of evolutionary systems and shortly reviews insights of evolutionary economics that are relevant to the present discussion. Section 3 considers evolutionary analysis in environmental and resource economics. Section 4 introduces evolutionary growth theories and compares these with neoclassical growth theories. Section 5 contains the core of the paper, which is an analysis of the relationship between growth and environment from an evolutionary perspective. Section 6 studies the question of whether growth can be considered as progress, and offers some policy suggestions. Section 7 concludes.

2. Evolutionary economics

Evolution, either genetic or non-genetic – as in economics –, involves a number of complementary core elements and processes (similar terms encountered in the biological and economic literature are shown between brackets):

1. *Diversity (variety, variation):* populations of agents, strategies, products or technologies.
2. *Selection:* processes that reduce existing diversity.
3. *Innovation (adoption):* processes that generate new diversity.
4. *Inheritance (transmission):* replication through reproduction or copying (imitation). It is the cause of durability and cumulative processes.
5. *Bounded rationality:* individuals and organizations (groups) behave automatically according to adapted or selected habits and routines, they imitate others, and are myopic.

Any evolutionary theory has to start from a population approach. This immediately clarifies an essential difference with traditional microeconomics, where the assumption of a representative agent is crucial. Contrary to common belief, such a microeconomics is not really as micro as is possible. In fact, evolutionary theories are 'more micro', because they describe populations with behavioral or technical diversity among individuals or firms.

A population approach can be operationalized in three different ways (van den Bergh, 2003). One is by way of aggregate variables, as is common in evolutionary game theory. This assumes that diversity is limited, or can be simplified, to sub-populations, each of which are assumed to be homogeneous. A second approach is by describing population distributions and changes therein. A third approach is disaggregate, and represents the most thorough micro-approach imaginable. It takes the form of multi-agent systems, in which each individual is explicitly described and can be assigned unique features. The agents can be defined in a setting of entirely random interactions ('gaseous cloud') or systematic interactions through a network structure or a spatial grid ('lattice'). Note that the traditional multi-agent (general equilibrium) and multi-sector (macroeconomic) models in economics, which are based on complementary and representative agents, are essentially different from multi-agent population models.

The fundamental mechanisms of any evolutionary process can be regarded as an 'accordion model'. It applies equally to genetic and non-genetic evolution. The basic idea is that evolution is both simple and powerful, being supported by opposite forces or causal processes. One force is the creation or generation of variation (or variety or diversity), which can be considered a disequilibrating force. A second force is selection or reduction of variety, which can be considered an equilibrating and directive force. The result of these opposite forces is similar to the movement of an accordion. Its dynamics depends crucially on the existing diversity and in turn changes it. The consequence of a sustained accordion movement is that structure and complexity emerge along a non-equilibrium dynamic path of change. This is nowadays best illustrated by experiments with computer simulation models in the field of evolutionary computation and modelling, which show that surprisingly complex structures can be generated with rather simple models of interactive innovation and selection (Bäck 1996).

An important implication of evolutionary change is that a system has so much diversity that it is extremely unlikely that it will revisit a previous state. In economics it is known as path dependence. In effect, it means that history is introduced. Indeed, a unique and important feature of evolutionary thinking is that it can integrate theory and history. As a result, evolution has turned out to be one of the most powerful ideas that science has generated, with a potentially very wide application area as well as synthesizing capacity (Ayres, 1994; Dennet, 1995).

Evolutionary economics is very much the legacy of Joseph Schumpeter, who is without any doubt the most influential of all early evolutionary economists and who wrote much about growth-related issues. Schumpeter questioned the static approach of standard economics, and showed a great interest in the dynamics of economies, in particular the capitalist system, in all of his major works. He considered qualitative economic and technological change in a wider context of social change, focusing on the impact of the innovative 'entrepreneur' (Schumpeter, 1934: first published in German in 1911). Schumpeter regarded economic (capitalistic) change as the result of revolutionary forces from within the economy, which destroy old processes and create new ones: "creative destruction". This allows for discrete or non-gradual changes, through clusters of derived innovations following a major invention. These themes were elaborated in his studies of business cycles (long waves). Schumpeter shares with Marx, Mill and Ricardo the general idea of a final steady state. In Schumpeter's case, this state is characterized by technological progress as the result of carefully planned team research under a socialist organization of society. Like Marx, Schumpeter gave thought to the process of change from the capitalist to the socialist economy. Although Schumpeter realized that discontinuities play a role, he did not assign to them the critical role that they have in Marx's theory. Instead, he believed that political responses would lead to a gradual transition. [1]

Since the 1950s, there has been a slow increase of publications on economic evolution. This can be partly explained by the success of evolutionary biology, the limits of neoclassical economics, and the search for evolutionary underpinnings of optimizing behavior as assumed by neoclassical economics. The most cited work since the 1950s has been that of Nelson and Winter (1982). The three building blocks of Nelson and Winter's theory of microevolution are organization routines, search behavior and selection environment. A routine can be considered as the equivalent of the gene in biological evolution, having some durability and being subject to change due to selection. A routine consists of a complex set of skilled individuals. Interactions between them are crucial, and depend on earlier contacts (learning, adaptation) and organization-specific 'language'. Routines create a constancy or continuity in the firm's behavior, due to factors such as organizational politics, avoiding conflicts, vested interests, financial costs of change, and management control. Change in routines follows two routes, namely organized search through R&D and non-directed and accidental change due to solving problems in the organization's performance – including old employees leaving and new ones entering. The framework supports bounded rationality as a general model, and suggests that deliberate choice with a given set of alternatives is a far cry from reality.

Various other, authentically evolutionary approaches have been proposed — perhaps with less impact (so far), but not necessarily less relevant. The most important recent proposal concerning the direction evolutionary economics should follow is without any doubt Potts (2000). Potts presents a kind of axiomatic foundation of evolutionary economics. In his view, economic systems are complex "hyperstructures", i.e. nested sets of connections among components. Economic change and growth of knowledge are in essence a process of changes in connections. New technologies, products, firms, sectors, and spatial structures arise that are more roundabout and complex than the old ones. Firm and economic growth are a process of creation of more complex organization, or new connections, as well as the grouping of those connections. In line with the idea of changing connections, Potts calls for a new microeconomics based on the technique of discrete, combinatorial mathematics, such as graph theory. This can be seen as support for multi-agent population models.

[1] Given the social-welfare states in most western countries with a mixture of private and public activities, markets and social institutions to redistribute income, and labor markets, unions and legislation, it seems that Schumpeter was closer to the truth than Marx. Of course, this is not true for an international setting as well as for certain low developed countries. Here a rather pure form of capitalism is found, characterized by extremely skewed distributions of income and power.

Neo-Schumpeterian theories of technical change currently dominate the evolutionary approach in economics (Dosi et al., 1988, Metcalfe, 1998). They regard innovation to cause asymmetry in technology among firms, sectors and countries, leading to exchange and trade. Comparative advantages are not fixed but change due to innovation and diffusion. Trade itself stimulates diffusion of knowledge. In addition, technological change affects the division of labor, the organization of intra-firm and inter-firm relationships, and thus the industrial structure and patterns of intermediate deliveries. Within the neo-Schumpeterian literature on technological evolution, the notion of path dependence has received much attention (Arthur, 1989). This is a result of increasing returns, which may be due to learning by using, bandwagon demand side effects (imitation), network externalities (e.g. telecommunication), informational increasing returns (if more adopted, then better known), and technological interrelatedness or complementarity. A consequence of increasing returns, or path dependence to one of multiple potential equilibria, is that inefficient equilibria can arise and a certain (inefficient) technology can become locked-in.[2]

A second current 'school', which is becoming more influential, is evolutionary game theory. It is also known as 'equilibrium selection theory', because it solves the problem of multiple Nash equilibria common in nonlinear economic equilibrium models (Friedman 1998). Evolutionary game theory is analytical, and can be so due to the fact that it adopts an aggregate approach to describing evolutionary economic phenomena. Usually, two groups are distinguished, reflecting minimal diversity. Groups are considered to consist of identical individuals; in this sense, evolutionary game theory really is a compromise between representative agent and fully-fledged evolutionary models. Interactions among individuals and between individuals and their environment are usually described through an aggregate replicator equation. This formalizes the idea that individuals with above-average (below-average) fitness will increase (decrease) their proportion in the population. Evolutionary games give rise to asymptotic equilibria, because no process of regular generation of diversity is assumed. As a result, selection completely dominates system dynamics. In other words, there is no interaction between innovation and selection, which makes evolution so characteristic and unique. A more suitable name for this approach theory would therefore be "selection game theory".

3. The intersection between evolutionary and environmental and resource economics

Economic evolutionary theories are incomplete due to their neglect of environmental dimensions. Important phases of economic history cannot be well understood without

[2] Evolutionary reasoning itself can be invoked to explain the slow spread of evolutionary thinking in economics. What follows then is that neoclassical economics is a case of lock-in at the level of scientific ideas. In fact, the Kuhnian notion of a paradigm is consistent with the notion of lock-in.

resorting to environmental or resource factors. The field of economics that focuses attention on these factors, environmental and resource economics, has been dominated by equilibrium theories in which individuals are assumed to maximize utility or profits, markets clear, and either no changes over time occur or they are of an aggregate and mechanistic type. This holds for the three core areas of environment policy theory, monetary valuation, and resource analysis. The recent adoption of the notion ‘sustainable development’ has meant a more explicit long-term focus, which can easily be regarded as an invitation to apply evolutionary perspectives, notably to address the complex role of structural and technological change in the conflict between economic growth and environmental preservation (Mulder and van den Bergh, 2001; Gowdy, 1999). Norgaard (1985) proposed to use the biological notion of coevolution as a joint and interactive evolution of nature, economy, technology, norms, policies and other institutional arrangements. Gowdy (1994) combines the notion of coevolution with macroevolutionary elements, noting that economic evolution is a process at multiple scales, which is consistent with hierarchical approaches to economic evolution.

Recently, Munro (1997) has added evolutionary elements to the standard problem of renewable resource harvesting. The motivation is that harvesting not only affects the quantity of the resource but also its quality, or composition in genetic terms. Examples can be found in agriculture (monocultures, and the use of pesticides and herbicides), fisheries (mesh size, season of fishing), ecosystem management (control of groundwater level, fire protection), and health care (use of antibiotics). The genetic-selective effects of resource use and habitat destruction provide a link with concerns for biodiversity loss. Munro formulates a dynamic optimization problem based on the notion that the use of insecticides raises the fitness of resistant insects relative to their susceptible competitors. The optimal use of insecticide is influenced by the evolutionary-selective dynamics of the system. Compared with this, the traditional optimal plan, which neglects evolution, can be characterized as myopic, thus giving rise to a too high level of pesticide use.

Much attention in environmental economics has been given to the risk of overexploitation of common property or common-pool resources, such as fisheries. Although common property is often confused with open access, where overexploitation is very likely, in common property resources the risk is also serious. It depends very much on the type of common property regime that is active, and may therefore differ from situation to situation. A fundamental question is whether it is useful to respond to resource conflicts and overuse with strict policies set by higher level governments, or that instead it would be better to rely on endogenous formation of use regimes. An evolutionary perspective has been used to analyze the latter, based on the idea that such regimes need to be sufficiently supported by the individuals participating, or, in other words, that a single norm evolves. Many contributions to this literature suggest that externally-imposed rules and monitoring can reduce and destabilize co-operation, or even completely destroy it. Instead, it is preferable to have a norm supported by communication among the resource users. When monitoring is imperfect, results are even worse, and stimulating norms through communication is certainly more desirable than external regulation. The latter is only desirable if an effective system of monitoring and sanctions can be implemented. However, self-organization in its most fundamental and general form is probably still not entirely understood. For instance, the size of the respective group seems to be important, but it is not clear what determines a critical size for (emergent) properties, such as particular norms or institutions, to arise. Instability in the evolutionary equilibrium can arise when certain parameters change (e.g. the resource price), or rules are implemented by an external regulator. In the latter case, norms may erode, ultimately leading to resource extinction. Equilibrium can also breakdown when sanctions decrease, harvesting technology becomes more productive (technical progress), or the price of the resource increases (Ostrom 1990). These issues have been examined using a wide range of approaches, including analyses based on evolutionary game theory (Sethi and Somanathan, 1996; Noailly et al., 2003), laboratory experiments and empirical field studies.

The examples given above suggest that environmental and resource economics have incorporated evolutionary elements. However, these examples are merely exceptions. Generally, environmental economics has neglected evolutionary issues, and evolutionary economics has neglected environmental issues (see further van den Bergh and Gowdy, 2000).

4. Evolutionary growth theory

This section aims to spell out the main assumptions and insights of evolutionary approaches to the analysis of economic growth, as well as to identify the main differences between endogenous and evolutionary growth theories.

At the basis of an evolutionary theory of economic growth is the notion of a population of heterogeneous firms. This gives rise to differential growth, which can be seen as a change in the frequencies of all possible individual characteristics. Nelson and Winter (1982: part IV, in particular Chapter 9) developed the first formal evolutionary model of economic growth, which is compared with Solow’s famous descriptive growth model from 1957. Its purpose is to generate and explain patterns of aggregate outputs, inputs and factor prices. Changes in the state of a sector follow probability rules, modeled as a Markov process with time dependent probabilities, that depend on search behavior, imitation, investments, entry and selection. If firms make sufficient profits, then they do not search or imitate others, otherwise they do. Search is local, implying small improvements and staying close to the present production technique. Imitation can focus on either the average or the best practice.

The output generated qualitatively resembles the real data used by Solow. Note that this evolutionary growth theory is based on the evolutionary theory of firms and industry structure proposed by Nelson and Winter, which consisted of routines, search and selection.

A crucial concept in neoclassical (exogenous and endogenous) growth theory is the aggregate production function. Nelson and Winter argue that: "… movements along the production function into previously inexperienced regions – the conceptual core of the neoclassical explanation of growth – must be rejected as a theoretical concept." Of course, the Cambridge capital debate had already assessed that it was a theoretical construct which gave rise to the internal inconsistency of growth theory (the implications for environmental economics are discussed in van den Bergh, 1999). Neither single firms nor the aggregate of all firms can move along an aggregate and continuous production function, because they possess only information or knowledge about a limited and discreet number of production techniques. This idea is also recognized by the neo-Austrian approach, which is formalized using an activity analysis type of model (Faber and Proops, 1990). The conclusion is that an aggregate production function, a standard and necessary element of neoclassical growth theory, is an artifact with no clear link to reality. It is certainly not in line with microfoundations (van den Bergh and Gowdy, 2003). Instead, evolutionary theories propose to avoid an aggregate production function and instead describe diversity of production relationships at the level of individual firms.

Nelson and Winter criticize growth accounting for explaining only about 20% of productivity growth, based on movements along an aggregate production function due to factor input changes, and leaving 80% as unexplained residual, often cleverly referred to as 'technological change', although sometimes partly attributed to environmental and resource factors. Instead, Nelson and Winter's approach makes it possible to integrate the micro- and macro-aspects of technology and its change over time. It generates results that are consistent not only with firms' decision making (routines, search), but also with empirical observations, such as aggregate data on factor level and efficiency features across sectors, and patterns of innovation and diffusion.

More recently, other formal evolutionary models of growth have been proposed (Conlisk, 1989; Silverberg et al., 1988). Conlisk works with a probability distribution of productivity of firms. The growth rate can be analytically derived as being dependent on the rate of diffusion of innovations and the size of innovations as indicated by the standard error of the productivity probability distribution. Silverberg et al. have proposed an evolutionary growth model that starts from the Goodwin model, which revolves around a formalization of the illustrious Philips curve that depicts the famous relation between wage change and unemployment level: the higher employment is, the higher the wage increase (inflation). The modeling of a population of a large number of firms and their behavior in terms of fixed rules generates the industry dynamics. An important behavior rule is that new capital follows from profit accumulation, where profit is redistributed so that relatively profitable types of capital accumulate relatively fast. This can be regarded as selection, in that a technique with a relatively high fitness spreads quickly, combined with a growing 'population of technologies' through accumulation. In order to complete the evolutionary dimension of the model, selection is complemented by a mechanism of innovation. The introduction of new firms and technologies in the economy follows from firms undertaking R&D to improve labor productivity, the outcome of which is stochastic (a Poisson process). The stochastic character is a way to reflect extreme uncertainty associated with innovation – in the form of surprises and ignorance. Spillovers are taken into account, through which a firm can profit from other firms' R&D, captured by economy-wide R&D. Firms can employ two strategies for innovation: mutation or imitation. The probability of imitation depends on the gap between the firms' own profit rate and the maximum profit rate in the population. This follows the general model of innovation and imitation as developed by Iwai (1984).

Empirical research on diversity has focused on the statistical analysis of country differences (Fagerberg, 1988). Important indicators used are input measures like R&D expenditures, and output measures like the rate of patenting. By combining these indicators with levels of productivity (income per capita), information clusters of countries can be identified. Some insights are that R&D and patenting turn out to be weakly correlated with productivity, that R&D does not guarantee successful patenting, and that growth rates can be inversely related to levels of productivity in the same period. The latter points to some catch-up mechanism, i.e. the idea that technological gaps are closed through imitation. The general Schumpeterian non-equilibrium approach emphasizes the interaction between opposing forces, consistent with the accordion model (see Section 2): innovation that increases technological differences among countries; and imitation and diffusion that reduces such differences.

Evolutionary versus endogenous growth theory

Here the main similarities and differences between evolutionary and (neoclassical) endogenous growth theories are briefly discussed, because both explicitly address the fact that growth is fuelled by technical change (see the Chapter by Smulders in this volume).

Both theories endogenize technical change (R&D) by using outlays on R&D as a core variable. Neoclassical theory defines R&D at the aggregate level. Evolutionary theory derives production as well as technical change from the population of firms, thus explicitly modeling R&D as being undertaken inside productive firms.

Related to this is the fact that neoclassical models depend crucially on an aggregate production function, thus reflecting macro-level theories, whereas evolutionary models start from firm populations, thus really reflecting micro-level theories.

Because of the population approach, evolutionary models can address behavioral and technical diversity or heterogeneity, whereas in neoclassical theories representative or identical agents are assumed. The latter is implicit in the argument that micro-level production functions can be replicated, resulting in constant returns to scale at an aggregate level (in the absence of positive R&D externalities).

Evolutionary models further assume bounded rationality, usually in the form of routines and learning through imitation. Neoclassical models assume, by definition, individual rationality (marginal decision rules) and social (intertemporal) optimality. This explains the neoclassical growth theory focus on equilibrium growth paths, as opposed to the non-equilibrium features of evolutionary growth. The approach of Aghion and Howitt (1992) incorporates some elements of heterogeneity and destructive or vertical innovation – creative destruction à la Schumpeter – in a neoclassical type of model, but maintains the assumption of the rational agent. Mulder et al. (2001) refer to this as a "neo-classical Schumpeterian approach".

Both theories can address uncertainty and irreversibility, although this is more common in evolutionary models. Evolutionary theories incorporate a particular type of irreversibility: namely, path-dependence (see Section 2). Neoclassical growth models, due to their level of aggregation, cannot address path-dependence, because it requires the use of a population model in which the distribution of characteristics follows a historical path, along which the distribution of characteristics (firms, technologies) irreversibly changes. Stochastic elements are common elements of evolutionary models, notably to specify the timing of innovations.

Neoclassical endogenous growth theory focuses attention on public externalities in technological innovation through the public good nature of certain aspects of knowledge and technology. In contrast, evolutionary theory focuses attention on the barriers and delays of diffusion of innovations, as well as the imperfect nature of replication and diffusion. Note that imperfect imitation itself is a cause of innovation.

As illustrated by Nelson and Winter (1982) and Conlisk (1989), evolutionary models can generate patterns quite close to those generated by neoclassical models with particular technological change assumptions. However, evolutionary growth models can generate other patterns as well as include more phenomena that are subject to public policy, such as diffusion (imitation) rates, firm-specific innovation factors, selection forces, and lock-in. Therefore, they can provide information about a wider set of policy instruments.

These insights are consistent with the general idea that evolution does not always imply growth, and vice versa. To see the first point, consider an evolutionary process in which the diversity of firms changes but the total output (in monetary or physical terms) is constant or even falling. The second point is illustrated by a (hypothetical) perfect replication of all productive activities in an economy, as is a common assumption underlying endogenous growth models.

Due to its lack of structural change, neoclassical growth theory cannot address time horizons beyond several decades. Stiglitz (1997) has suggested a time horizon in the order of 60 years. Seen from the perspective of long waves, traditional growth theory thus adopts a rather short time horizon. Note, for instance, that 60 years is about the periodicity of the Kondratieff cycle. Since evolutionary growth theory is suitable to deal with structural change, it can, in principle, be used to address longer time horizons.

In summary, the most important feature of evolutionary growth models is that they keep track of structural changes underlying growth by analyzing 'differential growth'. It is fair to say, however, that several of their 'promises' still need to be delivered. In addition, evolutionary growth analyses still suffer from ad hoc specifications or a lack of agreement on a common approach.

5. Evolutionary growth, environmental quality and resource scarcity

This section examines the implications of evolutionary growth theory for the debate on growth-versus-environment. Surprisingly, this debate and the recent related literature on sustainable development have neglected evolutionary considerations (Hofkes and van den Bergh, 1998). The dominant literature in economics on sustainable development focuses on deterministic equilibrium growth theory in which development is reduced to a non-historical and reversible process characterized by the accumulation of a one-dimensional capital stock (Toman et al., 1995). The following perspectives follow from evolutionary thinking.

In neoclassical economics, steady states and equilibria dominate. John Stuart Mill introduced the concept of a 'stationary state economy', which was later adapted to an environmental and resource context by Daly (1977). Evolutionary theory, however, suggests that sustainable development as a stationary state is unrealistic. Selection and innovation processes will continue to irreversibly change the structure of the economy, at the level of processes, products, firms, individuals, groups and regions. The economic focus on 'weak sustainability' and 'sustainable growth', allowing for a certain degree of substitution between economic capital and 'natural capital', may be a poor policy guide when uncertainty, irreversibility, and coevolution are taken into consideration (Ayres et al., 2001).

As argued in the previous section, evolutionary theory can, in comparison with economic growth theory, be regarded to extend the time horizon of analyses beyond decades and even centuries, which seems to be required by the goal of sustainable development. The need for a distant time horizon is especially relevant for research on climate change and biodiversity loss, as these are bound to significantly affect both natural and cultural-economic evolution.

Not surprisingly, climate change research is one of the few areas where (optimal) growth models have been actually 'applied' (Nordhaus, 1994), leading to considerable criticism (e.g. Demeritt and Rothman, 1999; Azar, 1998). The issues of uncertainty and irreversibility have been addressed in the traditional economic growth theory context by Kolstadt (1994), who added stochastic elements to Nordhaus' "DICE" model. The main insight obtained is that economic irreversibility due to over-investment in greenhouse gas (GHG) abatement techniques is more worrisome than irreversibility of natural processes like GHG accumulation in the atmosphere, climate change and ecological impacts. This is understandable, given the focus on economic efficiency of economic growth in a very simple, aggregate economy, and the neglect of uncertainty caused by future economic development.

A few studies have pursued evolutionary modeling in this area. Janssen (1998) and Janssen and de Vries (1998) have incorporated evolutionary elements in climate modeling by allowing adaptive agents to change their behavioral strategies as a result of changing perspectives, as a response to persistent surprises in global climate, represented by the global mean temperature of the atmosphere. These perspectives include "hierarchist" – complete control orientation, "individualist" – adaptive management orientation, and, "egalitarian" – preventive management orientation. The distribution of these perspectives in the population of agents (voters in a democracy) is changed according to a selection process modeled as a replicator equation based on an agent's fitness. This is a function of the difference or gap between expected temperature change and actual temperature change. In other words, when persistent surprises have occurred that cannot be made consistent with the initial perspective on the climate change system and problem, the agent's perspective adapts. This approach therefore tries to address the lack of complete and correct understanding of climate issues.

Faber and Proops (1990) propose a neo-Austrian approach with evolutionary elements, to emphasise the role of time. They allow for irreversibility of changes in the sector structure of the economy, for uncertainty and novelty, and for a teleological sequence of production activities ("roundaboutness"). The long-term relation between environment, technology and development is then characterized by three elements:

- The use of non-renewable natural resources is irreversible in time, so that a technology based on this must ultimately cease to be viable.
- Inventions and subsequent innovations lead to both more efficient use of presently used resources and substitution to resources previously not used.

- Innovation requires that a certain stock of capital goods with certain characteristics is built up.

They construct a multisector model with the production side formulated in terms of activity analysis, which allows to study the effect of invention and innovation on the transition from a situation with simple to more complex or roundabout production activities. Roundabout activities use multiple technologies. For instance, food production has become more roundabout, moving from agriculture with labor, through agriculture with labor and capital, to a large food processing industry with many intermediate deliveries. This approach can be extended with the technology effects of resource scarcity as indicated above. It can then simulate economic and environmental history from a pre-industrial agricultural society to an industrial society using fossil fuels and capital. It allows for a combination of continuous changes in technological efficiency and discrete jumps in the number of sectors and interdependencies among sectors.

An important question in the context of growth is whether technical innovation is subject to diminishing returns to scale? If one regards technical change as retrieving innovations from a limited set of potential innovations, then it would be subject to diminishing returns. One can, however, doubt whether this is true, notably when taking seriously the idea of Potts (2001) that evolution means additional connections and higher levels in systems. Hence, there does not seem to be a scarcity of innovations. Moreover, various strategies can counter diminishing returns, such as learning, enlarging the scale of activity, opening new markets, or seeking new applications. In addition, market mechanisms and profit seeking help solving problems of diminishing returns. When marginal returns from additional innovation and perfecting a product or process start to fall rapidly, firms will shift to new lines of R&D (product life cycle or technological regime; Nelson and Winter, 1982, p.258), be selected against (exit), or be taken over.

Some authors have argued that we already possess the technical knowledge to increase the efficiency of material and energy use by a factor of 4 to 10. Nevertheless, larger system changes seem necessary, which cannot be framed merely as design issues. Ehrlich et al. (1999) scrutinize the growth-optimist view that knowledge and technology increases will resolve environmental problems almost automatically. The journalist Horgan (1996) and the previous editor-in-chief of the highly respected journal *Nature*, Maddox (1998), present opposite views about the "knowledge explosion", with Horgan claiming that the rate of important scientific discoveries is decreasing and Maddox representing an optimistic perspective. More researchers than ever are doing basic and applied research, and in connection with this there is more communication of important innovations through journals and the internet than ever, leading to new (re)combinations or connections. Ehrlich et al.

argue, however, that there is also much disinformation, i.e. information that is incorrect, inaccurate or not adding new insights, and even a loss of information due to loss of biological and cultural biodiversity and other lost options.

Economic and environmental history from a coevolutionary angle

In Section 2, it was argued that evolutionary economics allows us to link theory to history. This section tries to consider such a link in the context of growth and environment.

An initial model of long-run historical change and environmental degradation may focus on important socio-economic transitions in human history, such as from hunting and gathering to agriculture to industrial societies. These have been argued to be consistent with the evolutionary theory of punctuated equilibrium, although so far this is no more than a loose conceptual connection (Somit and Peterson, 1989; Gowdy, 1994).

Another notion that has been suggested in the context of long-run changes is coevolution. This reflects an integration of elements from ecology and evolutionary biology. Although initially used at the level of species interactions, coevolution has since been invoked to denote a range of interactions: biological-cultural, ecological-economic, production-consumption, technology-preferences, and human genetic-cultural (Norgaard, 1985; Durham, 1991; Gowdy, 1994; van den Bergh and Stagl, 2003). An interesting typology of evolution comes from Durham (1991), who focuses on genetic-cultural interactions:

1. *Genetic mediation:* Genetic changes affect cultural evolution.
2. *Cultural mediation:* Cultural changes affect genetic evolution.
3. *Enhancement:* Cultural change reinforces natural evolution.
4. *Opposition:* Cultural change goes against natural evolution.
5. *Neutrality:* Cultural change is independent of biological evolution or selection.

According to Wilson (1998, p.128) “The quicker the pace of cultural evolution, the looser the connection between genes and culture, although the connection is never completely broken.” Nevertheless, it is difficult to prove that cultural change is independent from genes, since the indirect effects of certain aspects of culture on a population level cannot be easily traced empirically.

The above classification might be generalized to other types of coevolution, including the interaction of evolutionary economic and ecological systems. It should be noted, however, that coevolution is often used in a loose manner, without including aspects of populations and diversity.

Georgescu-Roegen (1971) identifies three technical ‘Promethean’ innovations that significantly altered the relationship between humans and their natural environment: fire, agriculture and the steam engine. It has been suggested that the invention of fire served to lengthen the day and stimulated late evening communication among humans, thus contributing to social-cultural evolution. This process accelerated after the last Ice Age (about 13,000 years ago), because of the development of sedimentary agriculture (the "Neolithic Revolution"), which led to the division of labor and specialization. Other major inventions, or "macromutations" (Mokyr 1990), include the windmill, the mechanical clock, the printing press, the casting of iron, the combustion engine, the airplane and the Green Revolution in agriculture.

Environmental factors may have influenced crucial changes during the social-cultural history of humankind. Potential environmental factors of influence were: local and global climate, diversity of soil conditions, scarcity of fuels (notably fuelwood), and available local plants and animals with sufficient concentrations of proteins, carbon hydrates, fats and vitamins. Diamond (1997) summarises the literature that supports the theory that climatic change and the availability of animal and plant species stimulated early domestication and thus agriculture and settlements. Diamond (1997: Chapter 10) emphasizes that sufficient diversity of agricultural experimentation was only possible in continents whose major axis was east-west oriented, as this would allow for the spread of agricultural technologies among regions with similar climates. This then is an important reason for the early 'economic success' of Eurasia. Diamond's theory thus explicitly relates early economic development to a combination of environmental-resource and geographical factors.

Wilkinson (1973) has developed an ecological theory of economic development with which he attempts to relate the Industrial Revolution to natural resource factors. This theory recognizes a number of human strategies to respond to resource scarcity, such as using new techniques, exploration of new resources, product innovation, and migration. Wilkinson's ideas imply an environmental perspective on the origins of the Industrial Revolution at the end of the 18th century. Agriculture and the use of fuelwood in iron smelting led to a loss of forest cover in England. A shortage of wood, reflected in a higher price, stimulated the early use of coal. Coal mining first occurred on outcrops at the surface, but soon shifted to deep mining. For this purpose groundwater needed to be pumped out, which meant the first serious application of the steam engine. Large-scale use led to the refinement of the steam engine, which in turn stimulated various spin-offs, notably in the textile industry and transport (ships, locomotives).

In a recent article, Galor and Moav (2002, p1) argue that: "… the struggle for survival that had characterized most of human existence generated an evolutionary advantage to human traits that were complementary to the growth process, triggering the take-off from an epoch of stagnation to sustained economic growth." This view fits in the "enhancement mode" of Durham's coevolution discussed above. At first sight, one might think that unlike genetic evolution of certain physical features that depend on variations of a single or few genes (lactose and gluten tolerance, sickle cell trait), the interaction between human genetic evolution and economic growth finds little support in evolutionary biology and theories of cultural evolution. The reason is that the evolution of human behavior involves so many genes that its timescale does not match that of economic growth. In particular, Galor and Moav's view seems to overlook the fact that economic growth is a phenomenon that arose long after *Homo Sapiens* had evolved (at least several hundred thousand years ago), and even much later than the rise of agriculture (about 13,000 years ago). Significant economic growth did not actually arise until the end of the Middle Ages, and sustained growth not until the Industrial Revolution was set in motion some 300 years ago.

Nevertheless, selection (and possibly recombination) effects may have changed the distribution of certain parental care characteristics, notably the trade-off between quantity of offspring and quality of parental care. In modern economic growth jargon, such quality improvements can be regarded as an early or even ancient type of investment in human capital. In particular, the gradual emergence of the smaller family since the rise of agriculture may have played an important role in this. Hitherto, larger groups, such as tribes built around one or more extended families, had a dominant influence on human evolution. Galor and Moav argue that human organization by way of smaller families fostered a strategy that focused relatively much attention on parental investment in quality of offspring, such as education. This, together with a sufficiently large size of the communicating human population, led, through technological innovation, to the essential impetus for the take-off of the Industrial Revolution. In other words, the authors propose an "endogenous evolutionary theory" of the Industrial Revolution. The selection pressure was effective during the preceding "Malthusian era" because the majority of people were living on a subsistence consumption level.

One explanation that the authors cannot exclude, however, is that the change in parental care has culturally rather than genetically evolved. This implies that the theory needs to be tested empirically, probably a difficult, if not impossible task. But perhaps this is not a really worrisome problem, because the theory works in quite a similar way for both cultural and genetic selection, and may even be formulated to include both. Finally, since the Industrial Revolution, the evolutionary incentives have changed, among other things, through institutionalized educational systems and requirements, as well as through incomes and consumption levels far exceeding subsistence levels. As a result, a new evolutionary regime applies nowadays, at least in the developed part of the world.

A complete view of macro-history involves, as well as growth trends, cycles or long waves. Long waves are caused by major shifts in methodology, due to fundamental advances in science. A rough classification of waves since the Industrial Revolution is shown in Table 1. Long waves have been accompanied by a number of changes. Among other things, the average size of firm has increased; the research (R&D) and innovation process has changed from firm to international levels; firm interactions and industry structure have altered; and, new key resources and related production sectors have appeared. In addition, each period has it peculiar environmental impacts, as illustrated in Table 1.

Table 1. Environmental and resource aspects of long waves

Phase	Key resources	Main environmental impacts
Hunter and gatherers	Wild animals and plants	Forest fires
Early agriculture	Solar energy	Soil erosion
Late Middle Ages	Wind, water	Local desiccation and water pollution
Early Industrial Revolution	Coal	Urban pollution
Steam power and railways	Coal	Factory pollution of water and air, large-scale infrastructure
Mass production	Oil, synthetics, heavy metals, fertilizers	Factory and car-related (noise, exhaust pollution, road infrastructure), toxic substances, acid rain
Second half 20th century	Oil, gas, heavy metals, tropical wood	Biodiversity loss, global warming
Future	Genetic resources, water ?	Genetic pollution, climate change, large-scale extinctions ?

6. Progress and policy in an evolutionary growth context

This section briefly addresses two questions: namely, whether growth can be considered as progress from an evolutionary perspective, and which environmental policy suggestions follow from evolutionary analysis.

The crucial question of whether evolution is identical to progress has no simple answer. An important reason is that evolutionary progress has been defined in many different ways (see Gowdy, 1994: Chapter 8; Gould, 1988; Maynard Smith and Szathmáry, 1995):

- *Increasing diversity:* Diversity is often considered to entail evolutionary potential or adaptive capacity in the face of environmental change.
- *Increasing complexity:* This can apply to the number of components, the number of connections among components, and the levels of nesting of such connections (Potts, 2000).
- *New ways of transmitting information:* In the economy, communication has gone through various phases: walking, horse, carriage, ship, train, car and plane, and telegraph, phone,

fax, and e-mail and Internet. The result is a larger population of communicating individuals.

- *More extended division of labor:* One aspect of the increase in complexity is a trend towards the extended division of labor, within natural as well as social-economic evolution.
- *Population growth:* From an evolutionary perspective, a species is successful if it dominates competitors, meaning dominance in ecosystems and control of its direct environment. This often goes along with growth in the size of population(s).
- *Increasing efficiency of energy capture or transformation:* Both in economic and biological systems, evolution can be related to energy processes (Buenstorf, 2000). From an ecological-evolutionary perspective, a rise in energy efficiency means less scarcity and less selection pressure, thus creating opportunities for (population) growth. Schneider and Kay (1994) state that open natural and economic systems tend evolve into more complex arrangements, so as to improve energy degradation and dissipation. This involves more energy capture, more cycling of energy and material, more complex structure, more energy stocking (biomass) and more diversity.

Maynard Smith and Szathmáry (1995) suggest that evolutionary history is better depicted as a branching tree rather than progress on a linear scale. There are indeed many reasons why evolution does not lead to progress (extending Campbell 1996, p.433):

1. Selection is a local search process, which leads at best to a local optimum and does not guarantee to generate a global optimum.
2. Organisms are locked into historical constraints. In economics, this is treated under the headings of path-dependence and lock-in (Arthur, 1989).
3. Adaptations are often compromises between different objectives, being stimulated by a multitude of selection forces.
4. Not all evolution is adaptive: randomness, (molecular) drift, coincidental founder effects, etc. all play an important role. In addition, macroevolution creates boundary conditions for adaptation and may destroy outcomes of evolution, i.e. in a way, set time back (‘initialize’).
5. Coevolution means adaptation to an adaptive environment. All straightforward notions of static or dynamic optimization are then lost; or, in the adaptive landscape metaphor, it means that the landscape changes underneath adaptive agents.

Sen (1993) notes that evolution as improving species does not imply improving the welfare or quality-of-life of each individual organism. Fitness is not a useful criterion for human progress, as it does not imply a happier or more pleasant life. Moreover, evolution as continuous change in diversity implies that inequality will arise again and again. Distributional change and inequality are inherent to evolution. Repeated selection for fitness implies that populations and species are continually stimulated to improve their fitness, since otherwise they are taken over by others (known as the "Red Queen hypothesis"; Strickberger, 1996, p.511). The relevance for economic growth can be seen by noting that welfare beyond (basic) needs is to a large extent relative, dependent upon the income and other features of individuals in a reference group. Without significantly changing the distribution of these features among individuals, economic growth is not necessarily equivalent with progress.

Policy issues

A fundamental consequence of evolutionary features like bounded rationality, non-equilibrium and path-dependence is that the normative part of neoclassical economics no longer holds. In particular, the correspondence of the market equilibrium and social welfare optimum (Pareto efficiency), formalized in the two fundamental theorems of welfare economics, is lost. This means that it is impossible to formulate an ideal blueprint of economic reality, to be implemented through planning or market approaches – since equilibrium theory on its own does not lead to a preference for either. Bounded rationality or alternative models of individual behavior lead to various particular policy suggestions that deviate from the standard economic theory of environmental policy (van den Bergh et al., 2000).

Evolutionary analysis of growth leads to a number of specific policy insights. A first one relates to technology. This includes instruments stimulating inventions, innovation and diffusion of technologies. In addition, two questions arise: How do regime shifts occur? And, how can they be stimulated? Linked to this is the specific problem of how to avoid lock-in of inefficient or undesired technologies, or, once this has occurred, how to 'unlock'. Preventing early lock-in requires portfolio investment. The unlocking of undesired policies – e.g. from an environmental perspective – cannot be realized by 'correcting prices', but requires a combination of policies from the following set:

- Reduce policy uncertainty.
- Set clear overall goal: *'zero emission' California*.
- Correct selective pressures: *car technology*.
- Create semi-protected niches: *solar energy*.
- Stimulate pathway technologies: *energy storage*.
- Stimulate diversity of R&D.
- Stimulate complementary technologies.

- Strive for technologies with flexible design and multiple options.
- Communicate with stakeholders to create a broad basis for learning and selection.

Creating a general goal and policy environment, such as in the case of the Zero Emission Mandate of California, can be regarded to provide a much stronger incentive for innovation than traditional environmental policy. Given the high degree of uncertainty faced by innovators, policy making should aim more at creating clear long-term goals and contexts, including at the global level.

A general strategy that derives from evolutionary reasoning is that, to assure adaptive potential in the face of changing environmental conditions, variety at various levels should be fostered: firms, technology, knowledge, R&D efforts, and 'schools' in science. Fisher's theorem is worthwhile mentioning here: "The greater the genetic variability upon which selection for fitness may act, the greater the expected improvement in fitness" (Strickberger, 1996, p.510). This theorem also explains why the propensity for variability will itself improve through repeated selection, i.e. variability itself is selected (Strickberger, idem). Focusing on a single best-available-technologies (BAT) is risky from this perspective, as knowledge about potential changes and impacts is always incomplete, and as it contributes to a lock-in of the BAT.

Evolutionary policy implications are not necessarily counter to, but are often overlapping with and complementary to, traditional policy implications. For instance, price based instruments, focusing on 'dynamic efficiency', are insufficient. Of course, if prices do not reflect positive or negative ,externalities too little R&D will be undertaken and lock-in will be reinforced. However, much more than price policy is needed to guide R&D and help unlocking. In the context of R&D policy, the trade-off between appropriability of the benefits of inventions and diffusion of inventions leads to the need for their patentability. Avoiding early lock-in of technologies with uncertain social and environmental effects requires, in addition to the above measures, policies to stimulate fair competition. Market structure has received much attention, both in neoclassical and evolutionary theory. Both theories recognize that large firms with market power, monopolies or oligopolies, are essential to generate R&D at such a scale as is necessary for certain types of innovations. The combined need for sufficient appropriability (market power) and diversity (competition) of R&D leads to a preference for an oligopolistic (supply side of the) market.[3] Note that the liberalization of energy markets, currently pursued by many countries, may be inconsistent with this insight, and may in fact slow down the pace of innovations in renewable energy technologies.

[3] Nelson and Winter (p.390), however, note that an oligopolistic market may also combine the worst features of monopoly and competition, notably since much R&D tends to be defensive, i.e. focused on imitating competitors.

Beyond a certain innovation scale, governments have to take control of R&D, through universities. This results in the link between R&D and profit making becoming too indirect or uncertain. Basic (university) research provides the basis of major technological changes, such as pathway technologies (macromutations, long waves), and can help avoid entering a path of diminishing returns. Relevant innovations from an environmental perspective are: decentralized energy production based on renewables (solar and wind energy); precision-biological agriculture and genetic technology; low pressure/temperature chemistry relying on catalysis; nanotechnology (dematerialisation, waste and emission reduction); and, battery electric vehicles. In addition, social or organizational innovations may need governmental support, such as car share or mixed car-public transport systems.[4] Pathway technologies, which have a large impact on many development and activities through connections to all kinds uses and other technologies, deserve much attention. For instance, energy storage is important, as it supports renewable energy use, solutions to electricity peak demand, and zero emissions car technology.

7. Conclusions

Evolutionary growth theory cannot be developed by simply incorporating new elements in existing growth theory, but requires a completely different set of assumptions. As opposed to evolutionary growth theory, exogenous and endogenous neoclassical growth theories are really macro-theories that lack explicit micro-relationships. The aggregation problem implies that there is no unique mapping from micro- to macro-level relationships. This is most clearly illustrated by the specification of an aggregate production function and an aggregate cumulative innovation indicator. The evolutionary perspective, on the other hand, starts from micro-level descriptions of populations of firms that work according to routines, search and selection. This results in non-equilibrium, differential growth with continuous interaction between innovation and selection of diversity. This in turn leads to a more intricate, as well as a more long-run relationship between resource scarcity, environmental conditions and economic growth than presented by neoclassical growth. A selection of insights is as follows:

- Growth is virtually always based on underlying structural change, at the level of changing distributions of technologies and firms. The long-run relationship between the economy and the environment needs to take explicit account of such structural economic changes,

[4] In addition, governments can change the selection environment for car producers: for example, through technical limits on motor size, speed and acceleration power. This would stimulate technological innovations leading to slower and lighter cars. This would have several advantages. Besides less use of materials and energy in production, less energy would be involved in collisions. This in turn might shift the attention in car construction from 'inside or passenger safety' or 'single car safety' to 'system safety': namely, by taking into account interactions among all cars. Against this background, relatively heavy cars imply a potential risk or a negative externality to other road users, and should as much as possible be banned or be subjected to an appropriate externality tax.

as these can lead to new patterns and interactions, which possibly can offer solutions to pressing environmental and resource problems that cause unsustainable growth.

- Scarcity of (energy or material) resources and environmental regulation directly affect the distribution of firm and technology characteristics, and indirectly aggregate economic activity. Since economic agents in evolutionary theory are characterized by bounded rationality, they will inefficiently use resources and environmental opportunities, as well as imperfectly grasp available opportunities for substitution of scarce by less scarce resources. Moreover, environmental regulation will not lead to optimal social welfare. Further, evolutionary insights are that transitions away from inefficient or outdated to new technologies are severely hampered or at best delayed by technological and organisational lock-in. All in all, the evolutionary perspective on environmental and resource limits to growth is much less optimistic than one based on neoclassical growth-cum-environment analysis.
- In addition, one should consider the issue of returns to technical change. If one regards it as retrieving innovations from a limited set of potential innovations, then it would be subject to diminishing returns. If, however, evolution is seen as 'additional connections' or more complex technologies and organizations, then there is not an obvious limit to innovations. However, it may be the case that more complex systems become less stable and more difficult to handle and maintain. Moreover, they may require more and more education from inventors and technicians, which is limited by the time available in an individual's life. Then fruitful innovations become increasingly scarce. Further, the tempo with which innovations arrive may go down.
- Major historical transitions, such as the rise of agriculture and the Industrial Revolution, have been influenced by environmental and resource conditions. The notion of coevolution is relevant for both historical and future growth analysis. This notion reflects that both the economy and the environment consist of diverse elements that change through innovation and selection, and are, moreover, interactive: the economy is adaptive to the environment and vice versa.
- Evolutionary growth is not identical with progress. Coevolution, local adaptation, and path dependence, among other things, suggest that evolution, at best, is caught in a local optimum. Furthermore, progress does not only depend on the absolute or average size of the economy (per capita) but also on changes in distribution, which are inevitable. Mere income growth is a too crude indicator to capture the wide variety of structural changes in an evolving economy.
- Changes in population distributions of technology give rise to path dependence, a historical process, which in turn can create the problem of lock-in of an undesirable

technology. Path-dependence and lock-in require a different approach than that suggested by the economic theory of environmental policy. Decentralized policy based on externality taxation (price regulation) is generally insufficient to unlock the system, except in the rare case where the marginal external cost is so high that the regulated price becomes prohibitive. Comparative statics results, which are common in equilibrium economics, provide insufficient information about which policy is needed, as desired equilibrium states may not be reachable from the present state.

- Because evolution means that the link between a social optimum and a market equilibrium is lost, optimal social welfare policies play a less central role in evolutionary economics than they do in neoclassical economics. On the other hand, evolutionary theory, due to its focus on population diversity, can better address distribution issues than neoclassical economics.

The present chapter has introduced a range of evolutionary economic ideas, which, although not elaborated in great detail, together suggest a fresh perspective on the relationship between growth, environment and resource scarcity. Evidently, further theoretizing, modeling and empirical research are needed. Given the small number of studies in this area, the added value of this line of research is expected to be very high.

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